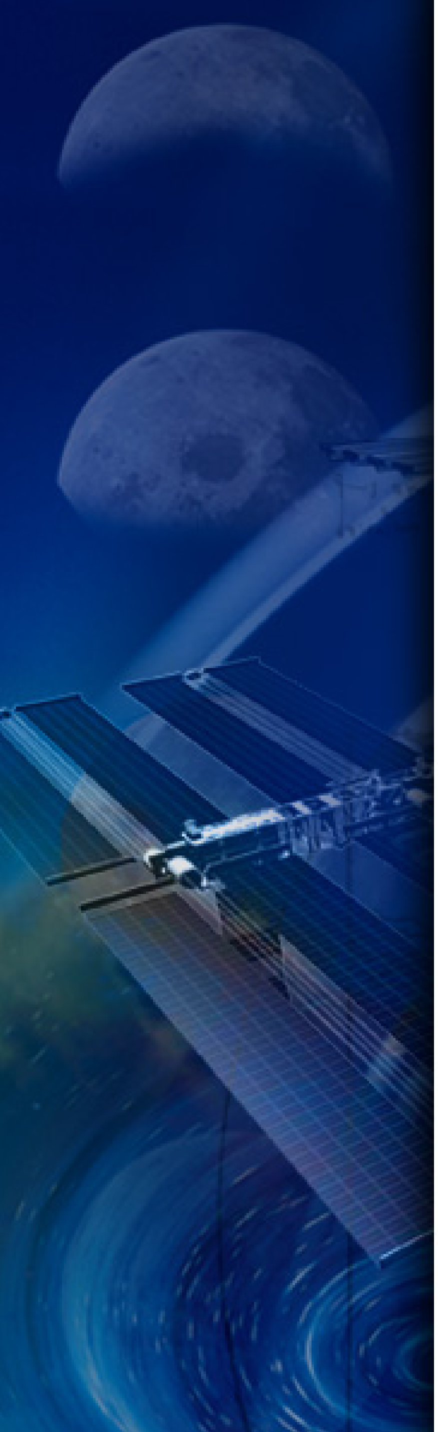

Calculation of Bubble Detector Response Using Data from the Matroshka-R Study

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15th WRMISS Workshop
Radiation Monitoring for the International Space Station
September 7-9 2010

Canadian Space Agency Agence spatiale canadienne

BTI BUBBLE Technology Industries

Canada

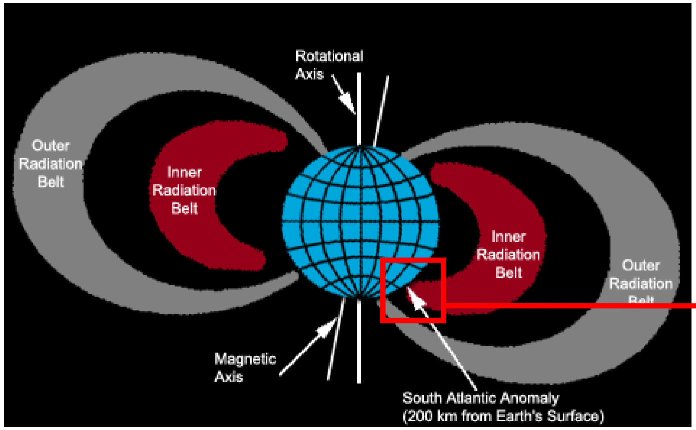
Motivation

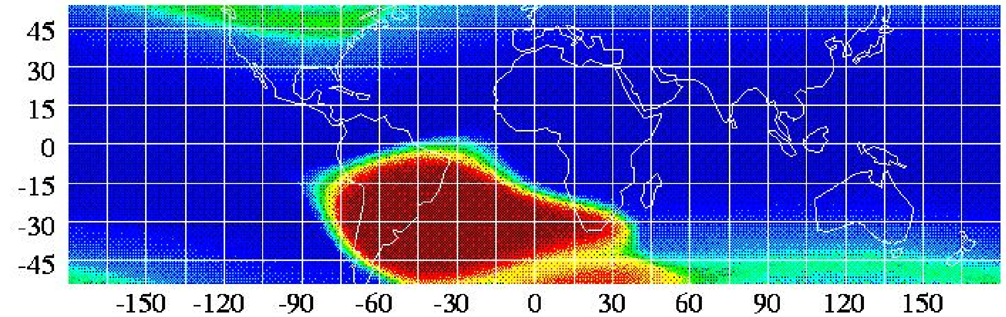
- In 2009, WRMISS asked Canadian Space Agency to prepare an overview paper on Bubble Detector Technology which would:
  - Highlight all the work and previous publications on Bubble Detector technology
  - Summarize data on Bubble Detector response to neutrons, protons, and HZE particles.

OUTLINE

- Introduction
- Bubble Detector Characterization Studies
- Mission Applications
  - Russian Matroshka-R
    - Session 8 : Proton and Neutron Studies
    - Session 7 : Heavy Ion Studies
- Contributions of Protons, Neutrons, and Heavy Ions to Bubble Count
- Conclusions

Introduction





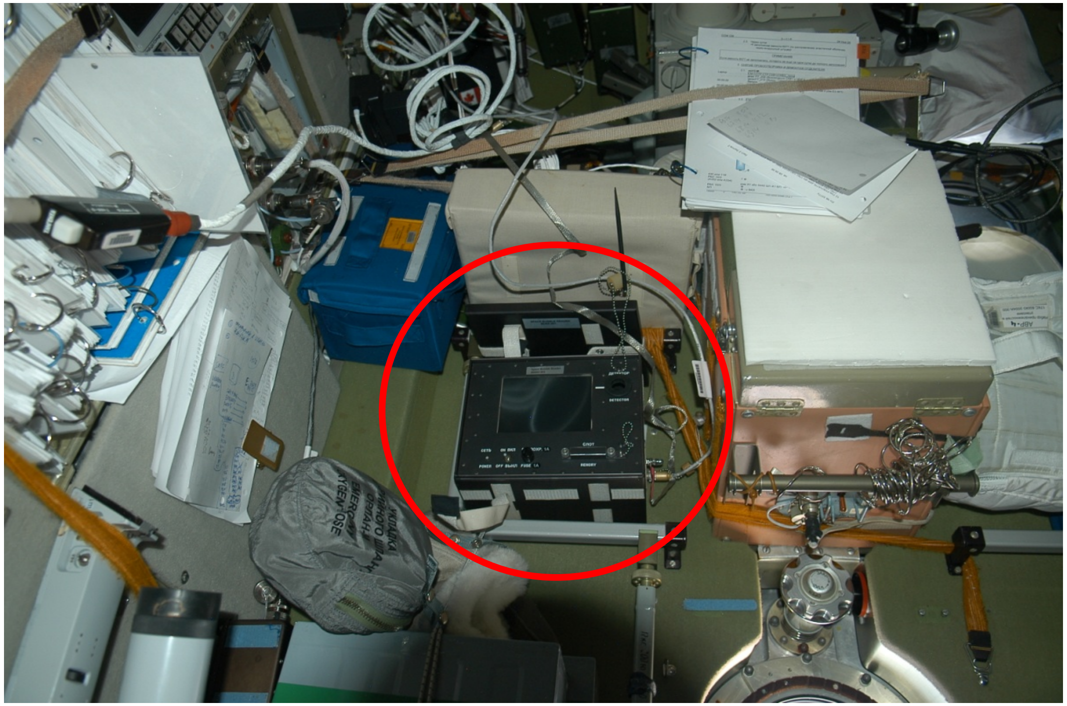
*NASA, ROSAT Guest Observer Facility, 2002 (http://heasarc.gsfc.nasa.gov/docs/rosat/gallery/misc_saad.html)

- There exists a complex particle and neutron field in space.
  - Albedo neutrons from Earth's atmosphere and secondary production from spacecraft shielding contributes ~10-30% of total dose equivalent.
    - TEPC reliable doses <20 MeV (response to higher energies?)
    - CR-39 passive dosimeters complement TEPC (and TLDs)

Introduction

- Space bubble detectors (SBD's)
  - Used in space applications since 1989, including Russian Matroshka-R (2006,-2008)
  - Test-tube-shaped neutron dosimeter developed by Bubble Technology Industries Inc. (BTI)
  - Microscopic liquid droplets form bubbles of trapped gas upon contact with neutrons.
  - Number of bubbles can be auto-counted using a reader and is indicative of the neutron radiation field intensity.

Bubble reader aboard the ISS Russian Segment



Source: Bubble Technology Industries http://www.bubbletech.ca/radiation_detectors_files/bdr.html

- Neutrons
  - Defence Research and Development Canada – Ottawa (DRDC-O) [1980's]
  - National Institute of Standards and Technology (NIST) [1990]
    - Thermal Neutrons (144 keV)
  - National Physical Laboratory (NPL) Van de Graff Accelerator [1990]
    - ^{7}Li(p,n) → 0.033 to 0.627 MeV
    - T(p,n) → 0.214 to 2.22 MeV
    - D(d,n) → 2.03 to 5.26 MeV
    - T(d,n) → 13 to 18 MeV
  - CERN/European Commission High Energy Reference Field (CERF) [2002]
    - Simulated space spectrum
    - Integral neutron field
  - iThemba [2007]
    - High energy neutrons (100 and 200 MeV)

- Protons
  - Tri-University Meson Facility (TRIUMF) [2003]
    - 81.7 MeV (as protons entered experimental apparatus)
    - 77 MeV (as protons entered the detector)
  - National Institute of Radiological Sciences (NIRS) [2004]
    - 35, 50 and 70 MeV
- Heavy Ions
  - Heavy Ion Medical Accelerator in Chiba (HIMAC) [2006]
    - Irradiated with N, Kr and Ar ions at 180, 400, and 500 MeV/u respectively.

Matroshka-R Experiments

- Performed over a series of experimental sessions
  - ISS-13 (Sessions 1 & 2) [2006]
  - ISS-14 (Sessions 3 and 4) [2007]
  - ISS-15 (Sessions 5, 6 and 7) [2007/2008]
  - ISS-16 (Sessions 8 and 9) [2008]

- Experiments performed using a spherical phantom with detectors placed on inside and outside of sphere.

Matroshka-R Experiments | Detector Locations for Sessions 7 and 8

- Session 7 (ISS-15) : phantom placed in the Russian docking module
  - B01, B02, B03 placed on surface of phantom
  - B04 located behind the phantom on outer wall of the cabin
  - B05, B06 located on internal wall of cabin

- Session 8 (ISS-16) : phantom place in the Russian PIRS module
  - B01, B02, B03 gelled to the surface of phantom
  - B04 located in the service module (SM) starboard cabin
  - B06, B07 were located in the SM, close to the astronaut working desk
  - B08 located in the SM (on the ceiling by the R16 radiometer)

Matroshka-R Experiments | Measurements for Sessions 7 and 8

Matroshka-R Results for Session 7						
Detector Label	**B01**	**B02**	**B03**	**B04**	**B05**	**B06**
Sensitivity (bubble/µSv)	0.123	0.117	0.111	0.111	0.099	0.093
Exposure Time (s)	6.09E+05	6.09E+05	6.08E+05	6.08E+05	6.09E+05	6.09E+05
Number of bubbles	99	98	94	106	104	71
Dose (µSv)	803	838	845	951	993	697
Dose Rate (µSv/day)	114	119	120	135	141	99

Maschrafi et al., Neutron Dose Study With Bubble Detectors Aboard the International Space Station as part of the Matroshka-R Experiment, Radiation Protection Dosimetry, Advance Access Publication, Vol. 133, No. 4, pp. 200-207, 2009

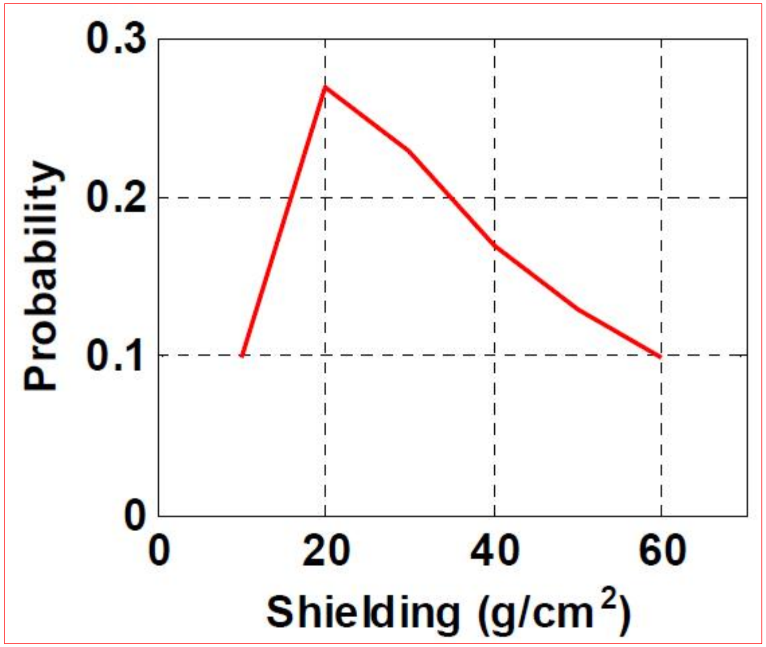
Matroshka-R Results for Session 8							
Detector Label	B01	B02	B03	B04	B06	B07	B08
Sensitivity (bubble/µSv)	0.123	0.117	0.111	0.111	0.099	0.093	0.086
Exposure Time (s)	4.47E+05	4.47E+05	4.47E+05	4.47E+05	4.47E+05	4.47E+05	4.47E+05
Number of bubbles	72	71	64	105	73	71	48
Dose (µSv)	585	605	574	947	740	766	554
Dose Rate (µSv/day)	113	117	111	183	143	148	107

Internal Report: Bubble Technology Industries Inc. (2009). *Matroshka-R Experiment Phase 2.* Chalk River, ON, Canada: Bubble Techology Industries Inc.

Analysis

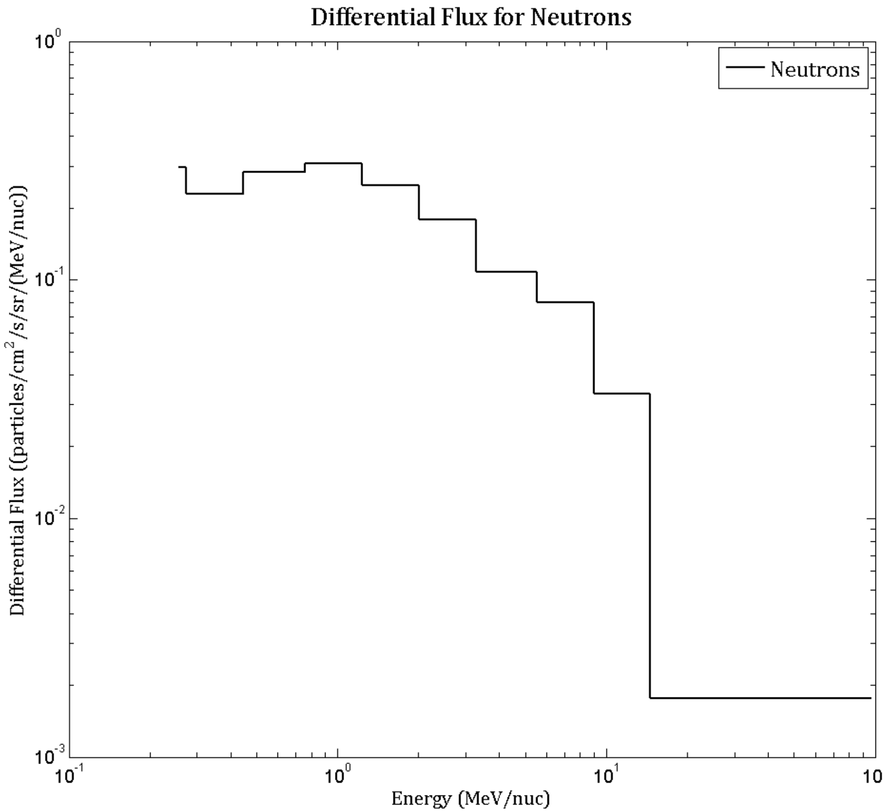
- Particle flux estimate (CREME96 with shielding function)
  - Differential flux: neutrons, protons and heavy ions (He, N, O and Ar)
  - Integrated differential flux:
    - Neutrons (0.25 – 100 MeV) → 1.70 x 10^5 neutrons/cm^2/s
    - Protons (10 MeV – 100 GeV) → 6.3 x 10^5 protons/cm^2/s
- Detector sensitivity S_d (bubbles/μSv)
- Particle sensitivity $S_{p,n}$ (b/(particle/cm^2)/(b/μSv))
- Experiment duration, t (s)
- 4π particle incidence

Shielding Function

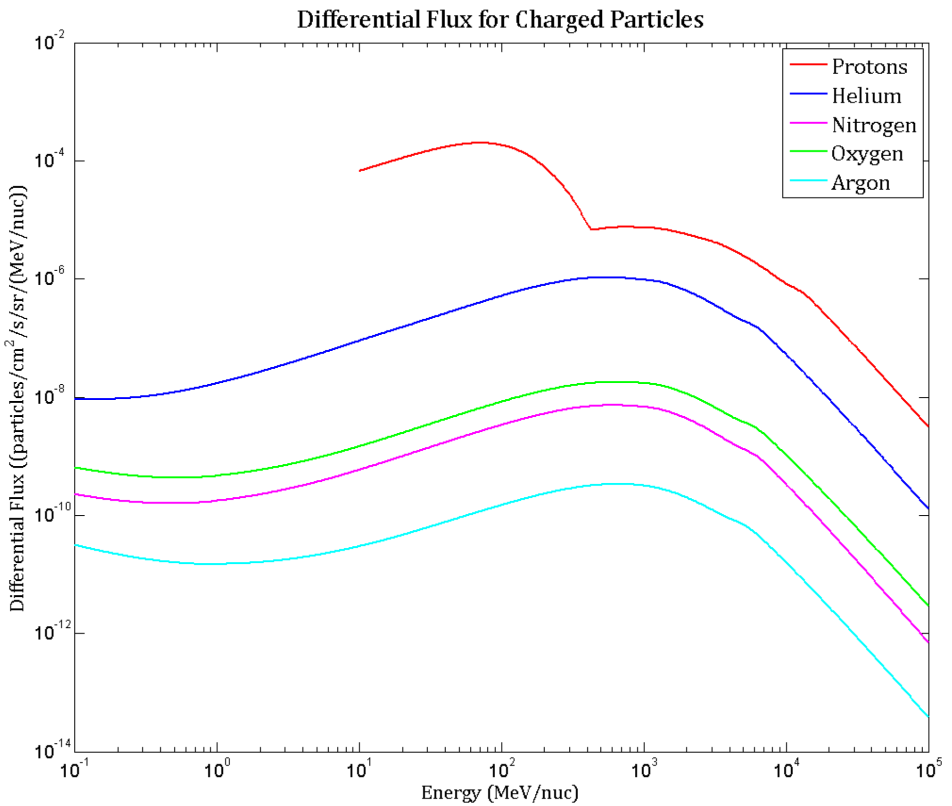


*Bubble Technology Industries, *Matroshka-R Experiment Phase 2 - FINAL REPORT*, August 10, 2010

Neutron and Charged Particle Spectra $\varphi_{n,p}(E)$



*Koshiishi et al, *Evaluation of the Neutron Radiation Environment Inside the International Space Station Based on Bonner Ball Neutron Detector Experiment*, Radiation Measurements, 2007, 1510-1520



*Charged particle differential flux from CREME96

Calculation Methodology

- Rate of bubble formation for protons (bubble/s)

$$\dot{N}_b = 4\pi S_d \int_{E_{lower}}^{E_{upper}} \varphi_p(E) S_p(E) dE \sim 4\pi S_d \sum_{10\text{ MeV}}^{100\text{ GeV}} \varphi(E) S_p(E) \Delta E$$

– Proton sensitivity (energy independent): S_p = 5.0 x 10^{-6} b/(p/cm^2)/(b/µSv)*

– Lower energy limit of 10 MeV (Proton penetration through detector shell)

*H. Ing and A. Mortimer, Advances in Space Research (1993)

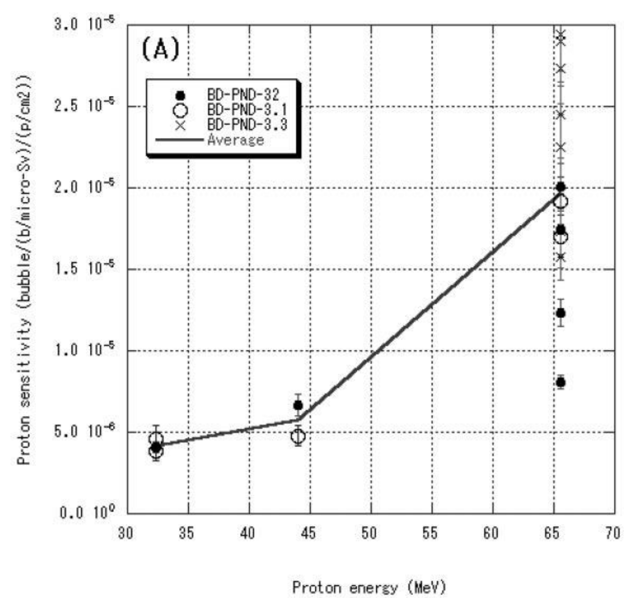
Calculation Methodology

- Protons contribute <1% to overall bubble count:

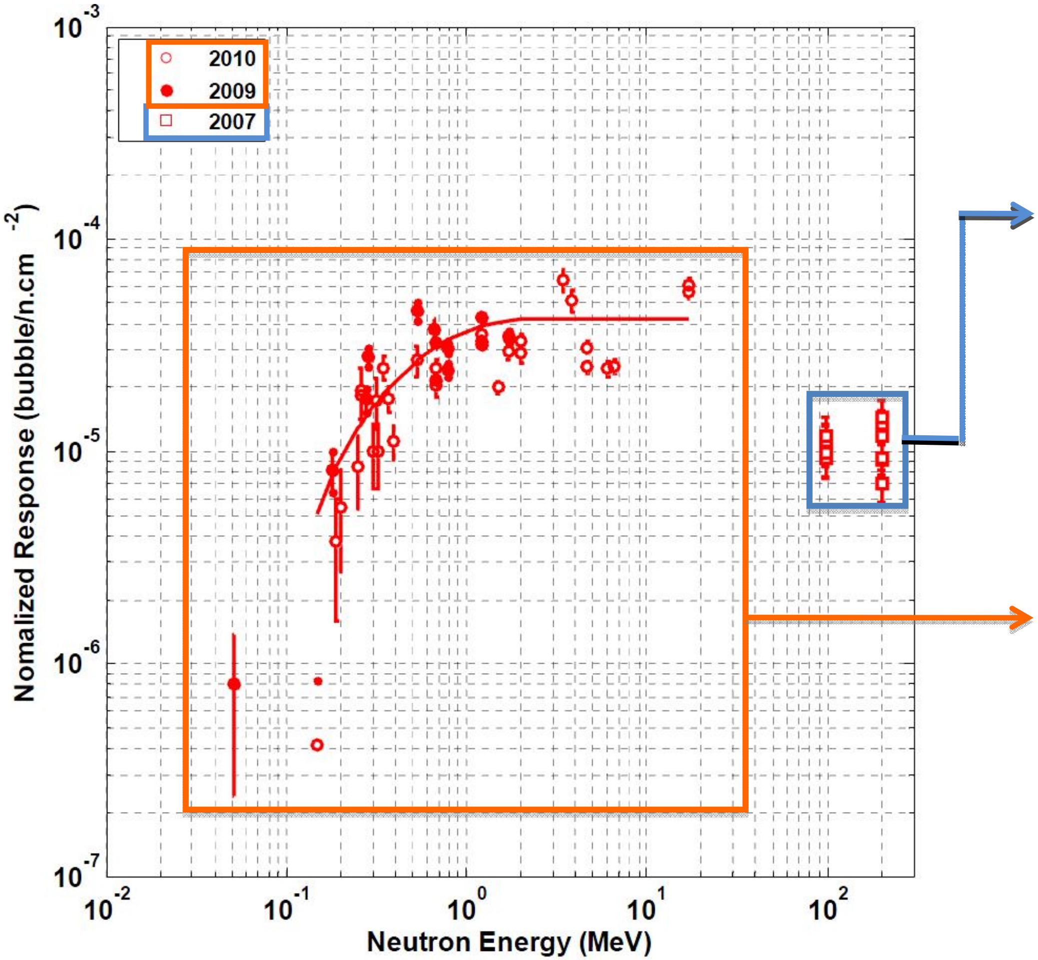
$4\pi S_p\ \Sigma\ [\varphi_p(E)\Delta E]$ (b/(b/μSv)/s)	Detector Label	S_d (b/μSv)		N_p (bubbles/s)	Time (s)		N (bubbles from protons)	# of bubbles determined from BTI Report	Proton Contribution %
4.49E-06	B01	0.123		5.52E-07	4.47E+05		0.25	72	0.34
4.49E-06	B02	0.117		5.25E-07	4.47E+05		0.23	71	0.33
4.49E-06	B03	0.111		4.98E-07	4.47E+05		0.22	64	0.35
4.49E-06	B04	0.111		4.98E-07	4.47E+05		0.22	105	0.21
4.49E-06	B06	0.099		4.44E-07	4.47E+05		0.20	73	0.27
4.49E-06	B07	0.093		4.17E-07	4.47E+05		0.19	71	0.26
4.49E-06	B08	0.086		3.86E-07	4.47E+05		0.17	48	0.36
						Mean:	0.21	72	**0.30**

Comparable results of ~1% using Takada response function for S_p*

*Takada et al, *Measured Proton Sensitivities of Bubble Detectors*, Radiation Protection Dosimetry, Vol. 111 (2), 181-189)



Neutron Response Function ($S_n(E)$)



High energy neutron sensitivities data collected at iThemba during experiments in 2007

Values averaged based on results of calibrations performed for the Radi-N study in 2009 and 2010

*Bubble Technology Industries, *Report on Characterization of the Space Bubble Detector Spectrometer*, March 31st 2010 (Detector sensitivity of 0.1 bubble μSv^{-1})

Predicted Versus Measured Bubble Count for Neutrons (Matroshka-R Session 8)

$$\dot{N}_b = 4\pi S_d \int_{E_{lower}}^{E_{upper}} \varphi_n(E) S_n(E) dE \sim 4\pi S_d \sum_{0.25\ \mathrm{MeV}}^{100\ \mathrm{MeV}} \varphi_n(E) S_n(E) \Delta E$$

4πΣ [φ_n(E) * Sn(E)*ΔE] (b/(b/μSv)/s)	Detector Label	Detector Sensitivity S_d (b/μSv)		# of Bubbles/s	Time Elapsed (s)		Total # of Bubbles due to Neutrons	Bubble Count during Matroshka-R	Measured Value/ Predicted Value
7.57E-04	B01	0.123		9.31E-05	447000		42	72	1.73
7.57E-04	B02	0.117		8.86E-05	447000		40	71	1.79
7.57E-04	B03	0.111		8.41E-05	447000		38	64	1.70
7.57E-04	B04	0.111		8.41E-05	447000		38	105	2.79
7.57E-04	B06	0.099		7.50E-05	447000		34	73	2.18
7.57E-04	B07	0.093		7.04E-05	447000		31	71	2.26
7.57E-04	B08	0.086		6.51E-05	447000		29	48	1.65
	Mean:	0.106				Mean:	36	72	2.01

- Reasonable agreement of number of bubbles predicted using neutron differential spectra from Koshiishi et al. with Matroshka measurement (factor of ~2).

Heavy Ion Contributions

- Calculations for Linear Energy Transfer (LET)
  - $P_{bf}(x) = 1 - e^{(-n\sigma x)}$
    - n = # of droplets per cm^3 (active volume of detector)
    - σ = cross section of droplet
    - x = critical distance the particle travels above threshold
  - Considers minimum and maximum energy to enter and pass completely through detector

- Calculations for Nuclear Interaction
  - X + ^{19}F interactions (scaled to p + ^{19}F) to determine heavy ion sensitivities
    - $\sigma_{pT} = \pi r_o \; ((A_p)^{1/3} + ((A_T)^{1/3} - b)^{1/2}$
      - σ_{pT} is cross section for interaction of projectile (p) and target (T) nuclei
      - $A_{p,T}$ is the mass number
      - b is the overlap parameter $b = 1.56 - 0.2((A_p)^{1/3} + ((A_T)^{1/3})^2$

Heavy Ion Calculation : LET

- Heavy ions contribute ~ 0.02% to overall bubble count due effect of linear energy transfer (LET):

Matroshka-R Results for Session 7

Detector Label	B01	B02	B03	B04	B05	B06
Sensitivity (bubble/μSv)	0.123	0.117	0.111	0.111	0.099	0.093
Exposure Time (s)	6.09E+05	6.09E+05	6.08E+05	6.08E+05	6.09E+05	6.09E+05
Number of bubbles	99	98	94	106	104	71
Dose (μSv)	803	838	845	951	993	697
Dose Rate (μSv/day)	114	119	120	135	141	99

*Bubble Technology Industries, *Matroshka-R Experiment Phase 2 - FINAL REPORT*, March 31st 2009, Revised: August 10th 2010

Heavy Ion Contribution for Detector B01:

Element	Ion Mass	Min Energy* (MeV)	Min Energy (MeV/nuc)	Max Energy** (MeV)	Max Energy (MeV/nuc)	Critical Distance (cm)	Bubble Formation Probability	$4\pi\Sigma$ of Integrated Flux (particles/cm^2/s)	Flux Ions (/s)	Bubbles due to Ions	Observed Bubbles	Bubbles due to Ions (%)
He	4	35	8.75	150	150	0.0035	1.88E-05	6.33E-05	3.37E-04	3.85E-03	99	0.00389
N	14	250	17.86	1000	71.43	0.121	6.50E-04	1.25E-06	6.66E-06	2.63E-03	99	0.00266
O	16	300	18.75	1300	81.25	0.181	9.72E-04	3.93E-06	2.09E-05	1.24E-02	99	0.01249
Ar	40	1100	27.5	5000	125	0.859	4.60E-03	1.52E-07	8.10E-07	2.27E-03	99	0.00229
											Sum:	0.02133

*Energy required to enter the detector
**Energy required to travel at least the length of the detector

Heavy Ion Calculation : Nuclear Interaction

- Heavy ions contribute ~ 0.03% to overall bubble count due effect of nuclear interactions:

Matroshka-R Results for Session 7						
Detector Label	B01	B02	B03	B04	B05	B06
Sensitivity (bubble/μSv)	0.123	0.117	0.111	0.111	0.099	0.093
Exposure Time (s)	6.09E+05	6.09E+05	6.08E+05	6.08E+05	6.09E+05	6.09E+05
Number of bubbles	99	98	94	106	104	71
Dose (μSv)	803	838	845	951	993	697
Dose Rate (μSv/day)	114	119	120	135	141	99

*Bubble Technology Industries, *Matroshka-R Experiment Phase 2 - FINAL REPORT*, March 31st 2009, Revised: August 10th 2010

Heavy Ion Contribution for Detector B01:

Element	Σ of Integrated Flux (particles/cm^2/s)	Ion Sensitivity (bubble/(bubble/uSv)(particle/cm2))	Sensitivity to Neutrons (bubble/uSv)	Bubbles due to Ions (/s)	Measurement Time (s)	Bubbles due to Ions	Observed Bubbles	Nuclear Interaction Contribution to Bubble Count (%)
He	4.55E-02	8.66E-06	0.123	4.84E-08	6.09E+05	0.0295	99	0.02978
N	3.07E-04	1.63E-05	0.123	6.17E-10	6.09E+05	0.0004	99	0.00038
O	8.36E-04	1.76E-05	0.123	1.81E-09	6.09E+05	0.0011	99	0.00111
Ar	1.45E-05	3.10E-05	0.123	5.52E-11	6.09E+05	0.0000	99	0.00003
							Sum:	0.03131

Summary

- The passive BD dosimeter developed in Canada has been used for neutron radiation monitoring in space since 1989
- During 2006-2008, BDs have been used in the Russian Matroshka-R study aboard International Space Station (ISS) during four expeditions (ISS-13, -14, -15 and -16).
- Using response data for neutrons, protons and heavy ions, based on comprehensive review of all literature bubble-detector data, along with differential-flux data calculated using the CREME code, calculations performed to determine contribution of charged particles to bubble formation
  - **Charged particles have a negligible overall contribution to the bubble count (< 0.5%)**

Key Points

- Protons below 10 MeV cannot penetrate the shell of the detector (SRIM Calculation)
- We have an isotropic flux in space (4π)
- We have come at the response function in two separate ways
  - We also folded in the response function measured at HIMAC by Takada
  - (differential flux derived with CREME96 with an appropriate shielding function (RUSSIAN) for charged particle spectrum + heavy ions
- We used the same methedology for neutrons and simply substituted in a differential flux measured with Bonner Sphere balls measured by the Japanese and a response function extended to high energy based on 100 and 200 MeV measurements at iThemba (got factor of 2)